

Swiss glacier recession since the Little Ice Age: Reconciliation with climate records

Arthur M. Greene, Wallace S. Broecker

Lamont-Doherty Earth Observatory of Columbia University

David Rind

Goddard Space Flight Center, Institute for Space Studies, New York

Abstract. Since the culmination of the Little Ice Age, Alpine glaciers have been in a state of general retreat. The present study, focusing on the Swiss Alps between 1850 and 1973, seeks to relate the concomitant rise in equilibrium-line altitudes (ELAs) to recorded climate shifts. The approach taken involves the development of a regression model, but differs from most other studies in that the relationship of (midlatitude) ELAs to climate is examined at a resolution such that regional values are treated as individual datapoints. Although such a treatment implies loss of resolution at small scales, a coherent relationship between climate and ELA is nonetheless obtained, due in large part to the primary control exercised by temperature, as well as the relatively wide range of ELAs included in the regression dataset. The derived relationship is applied to observed Swiss climate shifts, and is found to predict a secular rise in ELA somewhat greater than that observed. It is hypothesized that the difference represents climate change that had not yet been expressed by changes in glacier morphology.

1. Introduction

In a recent comprehensive survey of Swiss Alpine glaciation, Maisch et al. [1999, and pers. comm.] found that ELAs rose an average of 90m between the Little Ice Age glacial maximum (locally ca. 1850) and 1973. ELA was determined by the accumulation-area ratio (AAR) method, using an equilibrium AAR of 0.67, and the subsample of 549 glaciers from which the ELA rise was computed included only those with unbroken longitudinal profiles, presumed to present the least distorted response to climate shifts. This average over many points represents a well-constrained regional response to secular climate change, and offers an opportunity to examine the glacier-climate link as it applies on the large scale. To do this, a multiple regression model was developed utilizing gridded climate variables. The ELA dataset used spans the 30-60 degree latitude band in both hemispheres, and was smoothed to approximately the resolution of the climate data. Since this is comparable to the resolution of climate models, a useful ancillary result involves ascertaining the degree to which ELAs can be predicted from such data. The results suggest the possibility of a complementary statistical approach to the nested-model technique employed by Hostetler and Clark [1997] in their reconstruction of late Pleistocene glaciation in the western United States.

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2. Fitting the model

ELA data was gathered from a number of sources, including some compilations (see references). To increase homogeneity of response and minimize the effects of glacier-climate feedbacks only midlatitude datapoints were considered. Most glaciated areas in the 30-60 degree latitude band in both hemispheres are represented, for a population size of 52. Where descriptions made it possible to differentiate, only glaciers with unbroken longitudinal profiles were retained in the study. In a number of cases ELA datapoints for areas at subgrid-scale separation were averaged, in position as well as elevation, to produce a resolution comparable to that of the climate data. The mean observation date is 1976, with a standard deviation of 12.5 years.

The climate variables employed in the regression were derived from gridded datasets, each having a resolution of $2.5^\circ \times 2.5^\circ$, which, ipso facto, becomes the defining resolution for this study. It is the *spatial* variation of ELA and climate parameters that is employed in developing the regression model, which utilizes only climatologies. In computing the expected shift in Alpine ELA, the derived sensitivities are then applied to the *temporal* change in Swiss climate parameters. We justify this procedure by making only regional inferences regarding climate. Glaciers are thus treated as in situ measuring instruments, rather than as globally or even hemispherically representative climate proxies. Extending the interpretation of Swiss glacier behavior to these larger scales would require additional justification, which we do not offer here. Three climate parameters thought to exercise the predominant controls on ELA are tested in the regression: temperature, precipitation and cloud radiative forcing.

Since ELA is an *altitude*, we introduce temperature in a comparable form: the height of the atmospheric freezing level. This was computed from the NCEP-NCAR reanalysis data [Kalnay et al., 1996] for the years 1957-97, by linear interpolation between geopotential heights bracketing the zero degree level. Initially, two versions were prepared: a three-month summer mean (JJA or DJF, depending on hemisphere) and a six month warm-season mean (Apr-Sep or Oct-Mar). In preliminary regression experiments the latter proved to be more effective in explaining variance in ELA; it alone is retained in the analysis to follow.

Precipitation data were taken from an NCAR climatology for the period 1950-79 [Shea, 1986]. The predictor variable was computed in three versions: annual, cold-season (Oct-Mar and Apr-Sep, in the northern and southern hemispheres, respectively) and warm-season (the complementary 6-month periods).

An attempt was made to represent the altitude dependence of orographically forced precipitation, by defining a precipitation variable scaled by the difference between each ELA and the average land surface elevation in the surrounding $3^\circ \times 3^\circ$ box. However precipitation scaled in this manner was less successful than the unscaled original in explaining variance in the regression. Since stations tend to be located at lower altitudes than glaciers, it is likely that a precipitation bias due to altitude alone would be systematic. It should be noted, though, that topographic controls on precipitation are complex, and not solely altitude-dependent [Barry, 1981].

Finally, consideration was given to the effects of differential cloud cover on the surface radiation budget, by including a cloud radiative forcing dataset from the Goddard Institute for Space Studies (GISS). These data [Rossow and Zhang, 1995] were produced by processing cloud distributions obtained from the International Satellite Cloud Climatology Project dataset [Schiffer and Rossow, 1985] with the radiative transfer code used in the GISS general circulation model, and cover the years 1985–89. Three versions were prepared: longwave, shortwave and total radiative fluxes at the surface, each an annual mean. The fluxes are net, meaning that the effects of surface, as well as cloud albedo are considered in their computation, but the ice-covered gridbox fraction is small for most, if not all areas considered. Values for all climate variables were interpolated to the location of each ELA datum.

Trends exhibited by plots of ELA vs. predictor variables (see Figure 1a for an example) suggested the suitability of a linear model, which was employed. A best fit was obtained using only two predictors: warm-season freezing height and cold-season precipitation, with the coefficient of variation, $r^2 = 0.93$. The corresponding regression relation reads

$$ELA = 68 + 1.02FH - 0.90PC \quad (1)$$

where ELA and FH (warm-season freezing height) are expressed in meters and PC (cold-season precipitation) in millimeters. None of the cloud forcing parameters explained significant variance; for the moment we set them aside. FH is clearly the stronger predictor, explaining 89% of the variance in ELA if used as the only regressor, compared with 58% for PC. The t-statistics for the FH and PC coefficients are 15.5 and -5.0, respectively, indicating that both are statistically significant predictors.

Tests were conducted in which one fourth of the population (13 datapoints), selected at random, was held out as a validation dataset, and the regression recomputed using the remaining points. In ten such trials the squared coefficient of variation ranged from 0.91–0.96 and the squared correlation coefficient for predicted and observed ELA from 0.87–0.96, indicating that the model shows reasonably good predictive skill. Regression coefficients were stable, ranging from 0.98–1.07 for the FH and from -0.74 to -0.96 for the PC coefficient, the somewhat larger spread for the latter reflecting greater scatter in the precipitation data.

Sutherland [1984] describes a close exponential dependence between annual accumulation and ablation-season temperature at the ELA for a group of Norwegian glaciers, and indicates that similar relationships have been found to hold for other geographical areas. Such a relationship is employed by Dahl and Nesje [1992, 1996] in the interpretation of Holocene and Younger Dryas ELA shifts of Norwegian glaciers. While our regression model utilizes neither of these

parameters, it is nevertheless worth noting that cold-season precipitation is in fact correlated to some extent with warm-season freezing height ($r^2 = 0.43$), tending to decrease as the latter increases. A regression relationship whose precipitation term has been eliminated via this dependence does not show greater predictive skill than one derived from regressing ELA on freezing height alone. On the other hand, neither is the correlation strong enough to introduce serious multicollinearity in the regression. These conditions warrant the retention of the precipitation term in (1).

Dahl and Nesje [1992] have pointed out the importance of wind-transported snow in depressing cirque glacier ELA, relative to its regional value. To identify possible bias in the regression due to this effect, a test was conducted in which the 17 ELA datapoints provided by Peltó [1992], all of which were derived from cirque glaciers, were held out as above, and the remaining sites used to derive a regression equation. The mean and standard deviation for the prediction error, which was approximately normally distributed, were 37m and 317m, respectively. While the sign of the mean error is suggestive of the effect mentioned by Dahl and Nesje, the small t-statistic (0.47) indicates that the prediction error is not significantly different from zero, and thus that the effects of wind-drifted snow are not important (or equivalently, are below the noise level) for this dataset.

Departures of ELA from the warm-season freezing height are shown by offsets from the 1:1 line in Figure 1a. The standard deviation of the ELA-freezing height difference is 375m, so warm-season temperatures for most ELAs lie within two or three degrees of zero. In Figure 1b the effect of precipitation in lowering ELAs has been removed, using the PC coefficient from (1). It can be seen from these plots that deviations from the freezing height forced by precipitation are small, compared with variations in ELA forced by changes in the freezing height itself. Thus for this dataset temperature appears to exercise the primary control on ELA. Although the offset in Figure 1a might be reduced a priori by extending the “warm season” (and thus lowering the seasonal freezing line) it was felt desirable from a conceptual standpoint that ELA be related to temperature over a presumed ablation season; such a procedure was thus deemed unnecessarily arbitrary.

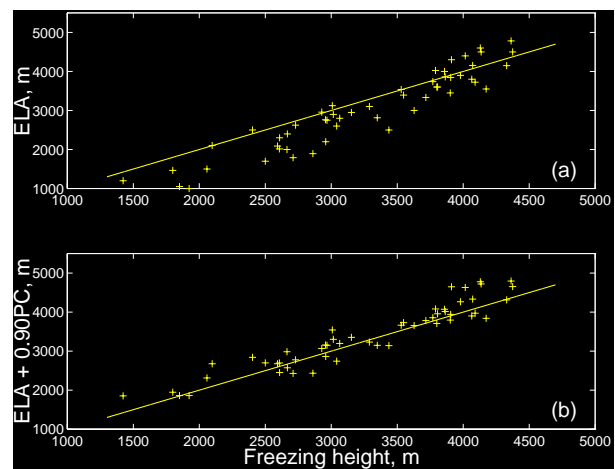


Figure 1. (a) ELA, and (b) Adjusted ELA (with the effect of cold-season precipitation removed) vs. warm-season freezing height. The lines have unit slope.

3. Secular shifts in Swiss ELA

Since there exists no continuous analog, over the time period of Maisch's glacier observations, for the radiosonde data on which the NCEP-NCAR atmospheric temperatures are based, secular changes in regional warm-season freezing height are investigated with the aid of station records. A precipitation history is derived from a gridded dataset of the same resolution as that used in the regression. Given the recorded climate changes, the shift in ELA predicted by the regression model is then compared with that observed.

The Global Historical Climate Network, v. 2 database [Peterson and Vose, 1997] contains six long station temperature records for the region 6–11E, 45.5–48N (Table 1), an area of gridbox scale covering most of Switzerland. These stations are located either in mountain settings or to the north of the Alpine chain, rather than in the Mediterranean climate domain to the south. A principal component analysis of their warm-season temperatures over the common period of record (1887–1973) identified a leading EOF accounting for 90% of the temporal variance in the data. Loadings for the individual records on this EOF (expressed as correlations) range from 0.91–0.97, indicating the presence of a coherent regional signal.

Secular temperature trends among the stations were found to vary systematically with elevation. The 1850–1973 plot (Figure 2a) spans a time interval corresponding to Maisch's ELA observations, but includes only the four longest records; Figure 2b, which includes two additional stations but only covers the period 1887–1973, is shown in order to substantiate the observation of increasing trend with altitude. To investigate temperature changes it is thus necessary to consider a trend at the appropriate elevation. Since the observations imply warm-season freezing heights somewhat below 2700m over the comparison interval, the record from station St. Bernard is most representative in this regard. This record shows a trend for the 1850–1973 period of $+0.66^{\circ}\text{C}/\text{century}$, amounting to a shift of 0.82°C between the nominal endpoints of Maisch's interval of observation. The Apr–Sep lapse rate between 850 and 700mb (ca. 1500–3000m elevation), interpolated to the center of the Alpine chain from the gridbox values at 45 and 47.5N, 7.5 and 10E is $6.2^{\circ}\text{C}/\text{km}$, as derived from the NCEP-NCAR data used in the regression, averaged over the years 1958–73. Figure 2a implies a slightly steeper lapse rate, about $6.4^{\circ}\text{C}/\text{km}$, for 1850. With these lapse rates, the St. Bernard temperature trend, as interpreted by the regression relationship, would produce an ELA rise of 153m over the interval of interest, not taking precipitation changes into account.

A regional precipitation record was derived from the dataset of Dai et al. [1997], again by interpolating gridbox values from 7.5 and 10E, 45 and 47.5N to a central position

Table 1. Stations with long temperature records in the region 6–11E, 45.5–48N.

Station	Lat (N)	Lon (E)	Elev (m)	Years of record
Basel	47.6	7.6	380	1755–1980
Geneva	45.7	6.9	107	1768–1997
Hohenpeissenberg	47.8	11.0	986	1781–1981
Säntis	47.3	9.4	2500	1883–1991
St. Bernard	45.7	6.9	2460	1818–1985
Zürich	47.4	8.6	556	1864–1997

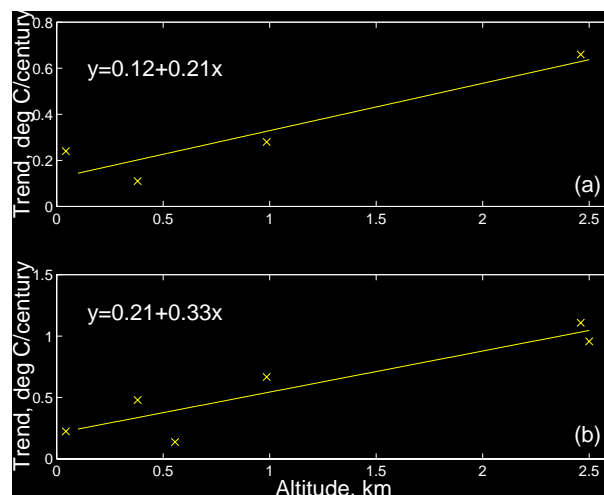


Figure 2. Temperature trend vs. altitude, (a) 1850–1973, for the four longest records, and (b) 1887–1973 for all six records. Both plots show trends increasing with elevation.

in the Alpine belt. For the period 1850–1973 this record shows a cold-season precipitation trend of $+35\text{mm}/\text{century}$, for a total change of 43mm. As mediated by the regression equation, this would reduce the predicted ELA rise to 114m, or 24m greater than the value given by Maisch. In the presence of an altitudinal gradient modern glaciers would receive greater precipitation, relative to that recorded by stations, than their 1850 incarnations, since their surfaces would have higher mean altitudes. Assuming this increase could be calculated, taking it into account would tend to lower the predicted ELA rise. However since the attempt to parameterize orographic precipitation (through the use of the scaled precipitation variable) was not successful, the resolution of such effects must be deemed beyond the capability of the present model.

Standard errors for the freezing height and precipitation coefficients are 0.067 and 0.18m/mm respectively, producing a standard error for the predicted ELA shift of 25m. For the observed shift, Maisch gives the sample standard deviation as 56m. When the many degrees of freedom associated with each estimate are taken into account, prediction and observation are found to differ at a very high confidence level. Thus the model is found to *overpredict* the observed ELA shift. Taking trend uncertainties into account as well (but assuming that FH and PC will tend to increase or decrease together, as suggested by the data) approximately doubles the standard error of the predicted shift, but does not alter this conclusion.

The adjustment of AAR-determined ELAs to changes in climate is mediated by ice flow, and necessarily involves a lag, or response time. For Swiss Alpine glaciers a reasonable estimate of the response time would be one to a few decades [Jóhannesson et al., 1989, Oerlemans and Fortuin, 1992]. This is not a well-constrained parameter, but we note that a response time of 24 years would be just sufficient to bring predicted and observed shifts into agreement. Accepting this as a reasonable value for the effective adjustment time of Swiss Alpine glaciers provides the required closure in the reconciliation of regional post-LIA climate and ELA shifts.

4. Summary and conclusions

The regression model indicates that the primary force driving the retreat of Swiss glaciers between the LIA maximum and 1973 was a rise in temperature, manifested as an increase in the atmospheric freezing height. A precipitation increase of about 10% produced a compensating effect, reducing the magnitude of the ELA rise by about one fourth. Only a portion of the inferred ELA shift had been realized as change in glacier geometry, and thus in AAR-determined equilibrium-line altitudes by 1973, owing to the finite adjustment time of glaciers, which we estimate as 24 years. The increase in temperature has apparently been more pronounced at higher elevations, implying a reduction of regional lapse rates over this period.

The strong coupling of ELA and warm-season freezing height is not totally unexpected, but it is satisfying that the relationship is here obtained from quite independent sources: ELAs from an assortment of field reports, and climate information from contemporary datasets. The effectiveness of precipitation as a predictor is somewhat reduced in this setting because of its variability on shorter spatial scales than temperature, and the consequent loss of information when averaging is carried out on the grid scale.

It has been implicitly assumed that glaciers respond directly to long-term trends, since these represent variation on time scales that are long compared with the glacier response time. However climate fluctuations may be considerable on intermediate time scales as well, some of which may be comparable to the response time. Thus it is probably unrealistic to assume, in effect, that the memory of glaciers extends all the way back to the culmination of the LIA, although this may be case for some of the larger ice bodies.

Cloud radiative forcing variables show negligible effect in explaining variance in ELA, probably because they are not truly independent. The best-correlated cloud variable (long-wave) explains 13 percent of the variance in ELA if used as the only regressor, but is also somewhat correlated with warm-season freezing height ($r = -0.46$). When combined in the regression (even without precipitation) the latter captures most of the available variance. Observations suggest that the radiative effects of differential cloud cover may well be present, but are probably small [see, e.g., Hastenrath, 1981]. Lastly, the dataset employed may be somewhat noisy, since it spans a comparatively short time.

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(* ELA data source)

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W. S. Broecker, A. M. Greene: Lamont-Doherty Earth Observatory of Columbia University, Palisades, NY 10964. e-mail: amg@ldeo.columbia.edu. D. Rind: NASA Goddard Space Flight Center, Institute for Space Studies, New York, NY 10025.

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